

Excess of pions with chiral symmetry restoration

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Abstract

We study the effect of the chiral phase transition on pion production in hot hadronic matter. The phase of restored chiral symmetry is characterized by the appearance of the scalar σ -meson as a chiral partner of the pion as well as by the degeneracy of the vector and axial-vector mesons. We find rapid thermal and chemical equilibration of these degrees of freedom in the symmetric phase. Provided that the chiral transition temperature is not considerably high, the presence of a chirally symmetric phase will result in ~ 1.6 times more thermal pions in the final state.

I.

Chiral symmetry, a symmetry of quantum chromodynamics (QCD) in the limit of massless quarks, is spontaneously broken in the ground state of QCD as indicated by the small mass of the pion [1]. At high temperatures chiral symmetry is expected to be restored, as shown by numerical simulations in lattice QCD [2] as well as model calculations [3]. However, some intriguing questions still remain on how chiral symmetry is actually restored in hot hadronic matter and what the signatures of the restored phase are. High energy nucleus-nucleus collisions offer a unique opportunity to explore the properties of hadronic matter at high temperatures and densities and to address these questions in experiment.

One way to study the signatures of the chiral phase transition in hot hadronic matter is by comparing the properties of the hadronic system in the broken phase with those in the symmetric phase. One of the interesting features of the symmetry restored phase is the appearance of the scalar σ -meson which forms a chiral multiplet with the pions. The σ -meson corresponds to an amplitude fluctuation of the order parameter, the quark condensate, while the pions are related to a phase fluctuation. At low temperatures where chiral symmetry is spontaneously broken, the σ -meson has very large width due to the strong decay channel into two pions. For that reason it is very difficult to observe any resonance peak in the scalar channel of the $\pi - \pi$ phase shift. In a recent analysis of the $I = 0$ S -wave $\pi\pi$ phase shift δ_0^0 , the existence of a σ resonance has been inferred with $m_\sigma = 535 \sim 650$ MeV [4].

On the other hand, as the quark condensate drops with increasing temperature, the mass difference of the σ -meson and pion becomes small. As a result, the decay width of scalar meson decreases because the phase space available for the outgoing pions is reduced. Close to the phase transition temperature T_χ , where the σ -mass has dropped below that of two pions, the decay channel closes and the σ becomes an elementary excitation. The observation of a narrow width scalar meson has been suggested as a direct signature of chiral symmetry restoration [5], but since the σ does not couple to any penetrating probes such as photons and dileptons this is difficult to observe in experiment.

The purpose of this paper is to study the effect of the σ -meson on the pion production in high energy nucleus-nucleus collisions. The pion production will depend on the thermodynamic equilibration conditions of a system during the evolution from hadronization to freeze-out. We will show that the chemical equilibrium conditions in the chirally symmetric phase are quite different from those in the broken phase mainly due to the appearance of the light σ meson and the drop of the chiral condensate. This will have some interesting consequence for the final state pion abundance.

II.

Let us consider the $SU(2)_L \times SU(2)_R$ linear sigma model in order to describe the hadronic system close to the chiral phase transition [6]. All the arguments presented below will only depend on the smallness of the chiral condensate and the σ -mass. Therefore, we will consider the system only in the hadronic phase – possibly close to the chiral phase transition temperature– and ignore effects from deconfinement. We furthermore assume that the axial $U_A(1)$ symmetry is not restored at the temperatures under considerations, which is supported by recent lattice calculations [7]. The linear sigma model includes isotriplet pseudoscalars (π^a), the pions, and the isosinglet scalar (σ). They form a $(\frac{1}{2}, \frac{1}{2})$ representation of $SU(2)_L \times SU(2)_R$, and are grouped into

$$\Phi = \frac{1}{2}(\sigma \mathbf{1} + i \boldsymbol{\tau} \cdot \boldsymbol{\pi}), \quad (1)$$

where $\mathbf{1}$ is the 2×2 unit matrix and the $\boldsymbol{\tau}$'s are the Pauli spin matrices.

We furthermore include vector ($\boldsymbol{\rho}^\mu$) and axial-vector (\boldsymbol{a}_1^μ) mesons as gauge fields and the total Lagrangian is given by [8,9]

$$\begin{aligned} \mathcal{L}_{eff} = & \text{Tr} D_\mu \Phi^* D^\mu \Phi + \mu^2 \text{Tr} (\Phi^* \Phi) - \lambda \text{Tr} (\Phi^* \Phi)^2 \\ & - \frac{1}{4} \text{Tr} (F_{L\mu\nu} F_L^{\mu\nu} + F_{R\mu\nu} F_R^{\mu\nu}) \\ & + \frac{1}{2} m_0^2 \text{Tr} (A_{L\mu} A_L^\mu + A_{R\mu} A_R^\mu) \\ & - h \text{Tr} (\Phi), \end{aligned} \quad (2)$$

where $A_L^\mu = (\boldsymbol{\rho}^\mu + \mathbf{a}_1^\mu) \cdot \boldsymbol{\tau}/2$, $A_R^\mu = (\boldsymbol{\rho}^\mu - \mathbf{a}_1^\mu) \cdot \boldsymbol{\tau}/2$ and

$$D^\mu \phi = \partial^\mu \phi + igA_L^\mu \phi - ig\phi A_R^\mu. \quad (3)$$

The last term is responsible for the explicit breaking of chiral symmetry due to the small but finite mass of the light quarks. μ , λ , g , and h are constants which are inferred by fitting the pion decay constant, the vector meson decay width, the sigma meson mass as well as the mass of the pion.

In the broken phase, at low temperatures, the scalar field has a non-vanishing vacuum expectation value, $\langle \sigma \rangle \equiv \sigma_0 = (\mu^2/\lambda)^{1/2}$, which plays the role of the order parameter of the chiral phase transition. After redefining the field $\sigma \rightarrow \sigma + \sigma_0$, one obtains massless Goldstone boson, $m_\pi = 0$, and a massive scalar meson, $m_\sigma = \sqrt{2\lambda}\sigma_0$ in the chiral limit, $h = 0$. The degeneracy between vector and axial-vector meson masses is also broken due to the finite expectation value of the σ -field; $m_\rho^2 = m_0^2$ and $m_{a_1}^2 = m_0^2 + g^2\sigma_0^2$.

Because of the spontaneous breaking of chiral symmetry, the derivative of the pion field contributes to the axial current and, therefore, the pion and axial vector field mix. To obtain physical fields we redefine the axial gauge fields as

$$\mathbf{a}_1^\mu \rightarrow \mathbf{a}_1^\mu - \frac{\chi}{Z} \left(\partial^\mu \boldsymbol{\pi} - ig[\boldsymbol{\rho}^\mu, \boldsymbol{\pi}] \right), \quad (4)$$

where $\chi = g\sigma_0/(g^2\sigma_0^2 + m_0^2)$. Z is the pion wave function renormalization constant and given by

$$Z^2 = 1 - \frac{g^2\sigma_0^2}{(g^2\sigma_0^2 + m_0^2)}. \quad (5)$$

In the broken phase we have a strong decay channel for the scalar meson into two pions, namely

$$\mathcal{L}_{\sigma\pi\pi} = -\frac{\lambda\sigma_0}{Z^2} \sigma \boldsymbol{\pi}^2 + \frac{g\chi}{Z^2} [\partial_\mu \sigma \boldsymbol{\pi} \cdot \partial^\mu \boldsymbol{\pi} - (1 - g\sigma_0\chi) \sigma \partial^\mu \boldsymbol{\pi} \cdot \partial_\mu \boldsymbol{\pi}] \quad (6)$$

where the parameter λ is determined by the sigma meson mass. It assumes a value of 21.4 (7.62) for $m_\sigma \sim 1$ GeV (0.6 GeV). With this coupling the resulting width is $\Gamma_{\sigma\pi\pi} \simeq 800$ (600) MeV.

In the chirally symmetric phase, the expectation value of the σ -field vanishes, $\sigma_0 = 0$. In this case, the σ -meson and the pions as well as the vector- and axial-vector fields form a degenerate chiral multiplet, respectively. As a consequence the decay of the σ -meson into two pions is kinematically forbidden. Also the vector and axial-vector current-current correlators will be identical, a property which persists at finite temperature [9].

Moreover, the coupling constants among the mesons will be modified in the symmetric phase since they depend on the strength of the scalar condensate. In the chirally symmetric phase we have

$$\begin{aligned}\mathcal{L}_{\pi\pi\rho} &\rightarrow g\boldsymbol{\rho}^\mu \cdot (\boldsymbol{\pi} \times \partial_\mu \boldsymbol{\pi}), \\ \mathcal{L}_{\pi\pi\sigma} &\rightarrow 0, \\ \mathcal{L}_{\pi\rho a_1} &\rightarrow 0, \\ \mathcal{L}_{\pi\sigma a_1} &\rightarrow -g\mathbf{a}_1^\mu \cdot (\sigma\partial_\mu \boldsymbol{\pi} - \partial_\mu \sigma \boldsymbol{\pi}).\end{aligned}\tag{7}$$

We can see that the coupling of σ meson to two pions vanishes, that is, the decay channel for scalar mesons into two pions is completely closed. Also the $\pi - \rho - a_1$ coupling vanishes in the chirally symmetric phase. Only vector and axial vector mesons decay into two pions, and pion and scalar meson, respectively. Since the couplings are proportional to the scalar condensate, they become already negligible once one gets close enough to T_χ *without* actually restoring chiral symmetry.

The dependence of the coupling constants on the chiral condensate leads to interesting consequences related to the chiral phase transition. For example the thermal photon production in hadronic matter would be affected considerably. The dominating production channel is believed to be the reaction $\pi\rho \rightarrow a_1 \rightarrow \pi\gamma$ [10] which is due to the interaction

$$\mathcal{L}_{a_1\rho\pi} = -\frac{g}{Z}\chi \left[(\partial_\mu \boldsymbol{\rho}_\nu - \partial_\nu \boldsymbol{\rho}_\mu) \cdot \partial^\mu \boldsymbol{\pi} \times \mathbf{a}_1^\nu + (\partial_\mu \mathbf{a}_{1\nu} - \partial_\nu \mathbf{a}_{1\mu}) \cdot \partial^\mu \boldsymbol{\rho}^\nu \times \boldsymbol{\pi} \right]\tag{8}$$

assuming vector meson dominance. This reaction is shut off in the symmetric phase since $Z \rightarrow 1$ and $\chi \rightarrow 0$ as the condensate (σ_0) vanishes, implying a suppression of the photon production in the chirally symmetric phase [11].

III.

In this section we study the consequences of the chiral phase transition related to the chemical equilibration of pions. To this end we will calculate the chemical equilibration times in the broken as well as in the chirally symmetric phase. Thermodynamic equilibration is driven by the multiple collisions among the particles in the system. When the collision rate is fast compared to the lifetime of the hadronic system thermodynamic equilibrium can be reached. In both phases, broken as well as symmetric, thermal, i.e. kinetic equilibration of pions is governed by elastic two-body collisions, $\pi\pi \rightleftharpoons \pi\pi$. At temperatures $T > 100$ MeV, this reaction is dominated by the strong p-wave isovector (ρ) channel. Since the coupling to the ρ -meson is not changed in the symmetric phase (see eq. (7)), this reaction will be equally strong in both phases. In addition, in the symmetric phase, the s-wave scattering will be considerably stronger than in the broken phase where these reactions are small due to the Goldstone nature of the pions. It has been shown that already in the broken phase elastic collisions are frequent enough for pions to maintain thermal equilibrium even at low temperatures [12]. Since there are the additional s-wave interactions in the symmetric phase, it is safe to assume that kinetic equilibrium will be maintained in both phases to a very good approximation.

Chemical equilibration, on the other hand involves inelastic processes which only contribute in the next to leading order of the low energy expansion. As we shall see in the following, the disappearance of some of the couplings (7) in the symmetric phase will lead to quite different chemical equilibration conditions from these in the broken phase.

A. In symmetric phase

$$(i) \pi\pi \rightleftharpoons \pi\pi\pi\pi$$

Chemical equilibrium is caused by the various inelastic, particle-number changing reaction. Contrary to the broken phase, we have strong s-wave $\pi\pi \rightleftharpoons \pi\pi\pi\pi$ interactions in the sym-

metric phase as shown in Fig. 1. This reaction leads to an *absolute* chemical equilibrium of pions in medium which is defined by $\mu_\pi = 0$ ¹. The chemical relaxation time is given by [14]

$$\frac{1}{\tau_{ch}} = \frac{4}{n_\pi^0} I_0(\pi\pi \leftrightarrow \pi\pi\pi\pi; T) \quad (9)$$

where n_π^0 is the pion density at equilibrium and

$$\begin{aligned} I_0(\pi\pi \leftrightarrow \pi\pi\pi\pi; T) = & \mathcal{S} \int \frac{d^3 p_1}{(2\pi)^3 2E_1} \int \frac{d^3 p_2}{(2\pi)^3 2E_2} \cdots \int \frac{d^3 p_6}{(2\pi)^3 2E_6} \\ & \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - \cdots - p_6) \\ & \times \sum_{1,2,\dots,5,6} |\mathcal{M}(\pi_1\pi_2 \leftrightarrow \pi_3 \cdots \pi_6)|^2 e^{-(E_1+E_2)/T}. \end{aligned} \quad (10)$$

Here \mathcal{S} indicates the symmetric factors. Here, and throughout this paper, we use the Boltzmann limit of the Bose-Einstein quantum statistics.

The calculation has been done ignoring the interference terms among the six different diagrams [13]. At a temperature $T = 180$ MeV we find for the chemical relaxation time $\tau_{ch} = 2.8$ fm corresponding to the couplings $\lambda = 21.4$ ($m_\sigma = 1$ GeV). Since the cross section is proportional to λ^4 the results strongly depend on the values of λ . From the result we can see that it might be possible for pions to achieve an *absolute* chemical equilibrium with $\mu_\pi = 0$ near the symmetry restored phase for large values of λ . However, the value, of the coupling λ depends on the assumed value of the mass of the σ meson, which is not well determined. Furthermore, higher order thermal effect may renormalize the value of λ . Therefore, we cannot make any definite statements about the possibility of an absolute chemical equilibrium in the symmetric phase.

There are also inelastic reactions involving vector and axial vector mesons such as $\pi\pi \rightleftharpoons a_1 a_1$ or $\pi\pi \rightleftharpoons \rho\rho$. These reactions, which would drive the system to an absolute chemical equilibrium ($\mu_\pi \rightarrow 0$), however, turn out to be as slow as in the broken phase, $\tau_{ch} \sim 7$ fm/c at $T = 180$ MeV [14].

¹For a definition of the meaning of a pion chemical equilibrium in the context of heavy ion collisions see ref. [14].

(ii) $\pi\pi \rightleftharpoons \sigma\sigma$

Next there is the reactions $\pi\pi \rightleftharpoons \sigma\sigma$ (Fig. 2). Processes involving the exchange of an axial vector meson (Fig. 2.a and 2.b) as well the the direct coupling of two pions to two sigma mesons (Fig. 2.c) contribute. The latter is given by

$$\mathcal{L}_{\pi\pi\sigma\sigma} = \frac{\lambda}{2Z^2} \sigma^2 \boldsymbol{\pi}^2 + \frac{g^2 \chi^2}{2Z^2} \sigma^2 (\partial_\mu \boldsymbol{\pi})^2. \quad (11)$$

These reactions lead to *relative* chemical equilibrium for which $\mu_\pi = \mu_\sigma$ but μ_π need not to be zero.

The *relative* chemical relaxation time is given by [14]

$$\frac{1}{\tau_{ch}} = 4I_0(\pi\pi \rightleftharpoons \sigma\sigma; T) \left(\frac{1}{3n_\pi^0} + \frac{1}{n_\sigma^0} \right) \quad (12)$$

where $I_0(\pi\pi \rightleftharpoons \sigma\sigma; T)$ is given by the similar form as that of Eq. 10 for the reaction $\pi\pi \rightleftharpoons \sigma\sigma$. In the calculation of the scattering amplitude we introduce a form factor for the vertex involving the exchange of axial vector meson, given by

$$F = \frac{\Lambda^2 - m_{a_1}}{\Lambda^2 - t} \quad (13)$$

where we use the values of $\Lambda = 1.7 \text{ GeV}$. The results for the relaxation time are shown in Fig. 3 as a function of temperature assuming that the degenerate masses of the scalar and vector mesons are $m_\pi = m_\sigma = 140 \text{ MeV}$ and $m_\rho = m_{a_1} = 770 \text{ MeV}$. Two different values of the $\lambda = 21.4$ and 7.62 are considered corresponding to $m_\sigma = 1 \text{ GeV}$ and 0.6 GeV respectively. We can see that the relaxation time is about $0.3 \sim 0.6 \text{ fm}$ at $T = 180 \text{ MeV}$ which is much shorter than the effective size of the hot matter, $R = 2 \sim 3 \text{ fm}$ [14]. This implies that pions will reach *relative* chemical equilibrium with respect to the reaction $\pi\pi \rightleftharpoons \sigma\sigma$ with $\mu_\pi = \mu_\sigma$ in the chirally symmetric phase.

In order to take into account thermal corrections to the effective mass of the mesons [9] we also show the chemical relaxation times for $m_\pi = m_\sigma = 220 \text{ MeV}$ and $m_\rho = m_{a_1} = 980 \text{ MeV}$ in Fig. 4. In this case the reaction times are considerably slower but it is still possible to reach chemical equilibrium near the critical temperature, which is $T_\chi \approx 220 \text{ MeV}$ in this model.

In addition, there are the decays and formation of the vector meson, which are according to eq. (7), $\rho \rightleftharpoons \pi\pi$, $a_1 \rightleftharpoons \pi\sigma$. Notice, that in the symmetric phase the a_1 could not decay into $\pi\rho$. These decays are fast and will lead to a relative chemical equilibrium characterized by $\mu_\rho = 2\mu_\pi$ and $\mu_{a_1} = \mu_\pi + \mu_\sigma$. Taking into account the relative equilibrium between pions and the σ meson, we arrive at the following chemical equilibration conditions in the symmetric phase: $\mu_\pi = \mu_\sigma$, $\mu_\rho = 2\mu_\pi$, $\mu_{a_1} = 2\mu_\pi$

B. In broken phase

Recently [14], we have shown that pions can easily reach a *relative* chemical equilibrium with the ρ -mesons while the reaction times leading to a *absolute* chemical equilibrium, i.e. $\mu_\pi = 0$ are too long to be effective at temperatures $T < 160$ MeV. For the reactions involving scalar mesons we expect a *relative* chemical equilibrium of pions with the σ -mesons through the reaction $\sigma \rightleftharpoons \pi\pi$, since the decay width of $\sigma \rightarrow \pi\pi$ is very large. Assuming *relative* chemical equilibrium between pions and scalar mesons the reaction $\pi\pi \rightleftharpoons \sigma\sigma$ is effectively identical to the reaction $\pi\pi \rightleftharpoons \pi\pi\pi\pi$ and, thus, leads to *absolute* chemical equilibrium. The same reaction channel has been considered in the symmetric phase and shown to be very fast. In broken phase the dominant contribution comes from the pion exchange diagrams as shown in Fig. (2.d) and (2.e). However, the leading contribution proportional to λ^4 is canceled by the diagrams with four pions as in Fig. 1 and the result is very similar to that obtained in chiral perturbation theory [15], which is $\tau_{ch} \simeq 200$ fm.

In the broken phase at a temperature of about $T \sim 160$ MeV, therefore, a *relative* chemical equilibrium is maintained and it is characterized by $\mu_\sigma = 2\mu_\pi$, $\mu_\rho = 2\mu_\pi$, $\mu_{a_1} = 3\mu_\pi$. This is different from the conditions in the symmetric phase.

IV.

Finally, we study observable consequence of the different chemical relaxation conditions in the broken and symmetric phase. In the symmetric phase, $m_\pi = m_\sigma$ and $\mu_\pi = \mu_\sigma = \mu$.

Therefore, we will have as many σ mesons as one third of pions,

$$N_\sigma = \frac{1}{3}N_\pi = \frac{1}{3}\left(N_{\pi^+}(T, \mu) + N_{\pi^-}(T, \mu) + N_{\pi^0}(T, \mu)\right) \quad (14)$$

Similar for the vector mesons we have $m_{a_1} = m_\rho$ and $\mu_{a_1} = 2\mu_\pi = \mu_\rho$. Thus there are as many a_1 mesons as ρ mesons in the symmetric phase.

In the broken phase, on the other hand, we have $\mu_\sigma = 2\mu_\pi = 2\mu$ and $m_\sigma \gg m_\pi$ and, therefore,

$$N_\sigma \sim e^{-m_\sigma/T} \ll N_\pi, \quad (15)$$

as long as $\mu_\pi \ll m_\sigma$. For the vector and axial vector mesons the chemical equilibrium conditions are $\mu_\rho = 2\mu_\pi$, $\mu_{a_1} = \mu_\pi + \mu_\rho = \mu_\pi + \mu_\sigma = 3\mu_\pi$.

Given the same chemical potential in both phases, there will be more sigma mesons and axial vector mesons in chirally symmetric phase than in the broken phase simply due to the mass difference. This abundance can be observed in the final state pion number, if all inelastic channels, except the decay process, $\sigma \rightleftharpoons \pi\pi$, $a_1 \rightleftharpoons \pi\rho$, are inactive as the system passes through the broken phase. For a simple estimate we assume a chirally symmetric phase at the early stage of the hot matter with $\mu_\pi = 0$. Since all resonances decay into pions the observed pion number will be

$$\begin{aligned} \bar{N}_\pi(T_f) &= N_\pi(T_h) + 2N_\sigma(T_h) + \dots \\ &\approx \frac{5}{3}N_\pi(T_h) + \dots \end{aligned} \quad (16)$$

where we use the fact that $N_\sigma = \frac{1}{3}N_\pi$. Here we do not show the contribution from a_1 mesons explicitly since $N_{a_1} \ll N_\pi$. T_h is either the hadronization temperature or initial temperature of the hot hadronic matter and T_f is the freeze-out temperature. Alternatively, let us assume that there is no chirally symmetric phase at the initial stage of hot hadronic matter. Since the number of sigma mesons is almost negligible the observed pion number will be

$$\bar{N}_\pi(T_f) \approx N_\pi(T_h) + \dots \quad (17)$$

When there is a chirally symmetric phase initially, thus, we have about 1.6 times more thermal pions.

However, this result will be modified when there are pion number changing reactions in the system at low temperatures. In our previous work [14], we have shown that the reaction rates for the pion number changing processes will depend on the pion chemical potential as well as temperature. If we assume a chirally symmetric phase initially, which then turns into a phase of broken symmetry where the mass of the σ -meson is large, the number of σ -mesons will be oversaturated. These σ -mesons will rapidly decay leading to a finite chemical potential for the pions. Similarly, since the mass of the a_1 mesons increases as chiral symmetry gets broken, they also will be oversaturated leading to an additional increase of the pion chemical potential.

To estimate the induced pion chemical potential we assume that the chiral condensate instantly build up at $T = T_\chi$ and $\mu_\pi = 0$ initially. Since the effective number of pions should be constant at temperatures both slightly above ($T = T_\chi^+$) and below ($T = T_\chi^-$) the critical temperature, we have

$$\bar{N}_\pi(T_\chi^+, \mu_\pi = 0) = \bar{N}_\pi(T_\chi^-, \mu_\pi) \quad (18)$$

where $\bar{N}_\pi(T) = N_\pi + 2N_\sigma + 2N_\rho + 3N_{a_1}$. From this we have $\mu_\pi = 55 \sim 66$ MeV at $T_\chi = 160 \sim 200$ MeV, respectively. If $T_\chi \sim 160$ MeV the chemical relaxation time of pions, with $\mu_\pi = 55$ MeV, will be about 3 fm and is comparable to the effective size of the hot hadronic system [14]. If the chiral phase transition occurs at higher temperature than $T = 160$ MeV pion number changing processes will be active and the number of pions will be reduced. Thus we expect less pions than that obtained when we completely neglect the pion number changing processes as long as $T_\chi > 160$ MeV.

V.

In summary, we have studied the chemical equilibration conditions of pions in hot hadronic matter assuming chiral symmetry restoration. The chirally symmetric phase is

described with light scalar mesons which are degenerate with pions, and with degenerate vector and axial-vector mesons. In the symmetric phase a *relative* chemical equilibrium among the particles will be established rapidly, leading to $\mu_\sigma = \mu_\pi$ and $\mu_\rho = 2\mu_\pi = \mu_{a_1}$. The number of scalar mesons is then given by one third of the total number of pions at the given temperature. This is quite different from the situation encountered in the broken phase, where $\mu_\sigma = 2\mu_\pi$ and $\mu_{a_1} = 3\mu_\pi$.

This difference in chemical equilibration conditions of pions might lead to the excess of pions at freeze-out. As temperature decreases and the symmetry is broken scalar mesons become heavier and decay into two pions. Also a_1 mesons decay into three pions. The number of observed pions will be given by the number of pions plus contributions from the resonance decay. When we include the scalar and a_1 meson contributions to observed pions, we have ~ 1.6 times more pions compared to the case when there is no chiral phase transition. This, however, can only be observed, if the chiral transition temperature is not too high, $T_\chi \leq 160$ MeV. Otherwise, pion number changing processes in the broken phase will absorb the excess obtained from the chiral phase transition.

Finally, let us conclude by pointing out that an analysis of the particle abundances measured at SPS-energy heavy ion collisions found an excess of pions by a factor of 1.6 over the expected thermal value [16]. However, a different analysis based on the same data, does not find such an excess of pions [17].

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FIGURES

FIG. 1. Diagrams for inelastic scattering reactions, $\pi + \pi \leftrightarrow \pi + \pi + \pi + \pi$. There are diagrams not shown explicitly, which can be obtained by interchanging the final state.

FIG. 2. Diagrams for inelastic scattering reactions, $\pi + \pi \rightarrow \sigma + \sigma$. The solid line, double solid line and wave indicate pion, sigma meson and axial vector meson, respectively.

FIG. 3. Chemical relaxation time of pions at finite temperature. The results are obtained in the chirally symmetric phase with $m_\pi = m_\sigma = 140$ MeV and $m_\rho = m_{a_1} = 770$ MeV. Two different values of $\lambda = 21.4$ (lower), 7.62 (upper) are used.

FIG. 4. Chemical relaxation time of pions at finite temperature. The results are obtained in the chirally symmetric phase with thermal effects on the meson mass, $m_\pi = m_\sigma = 220$ MeV and $m_\rho = m_{a_1} = 980$ MeV. Two different values of $\lambda = 21.4$ (lower), 7.62 (upper) are used.

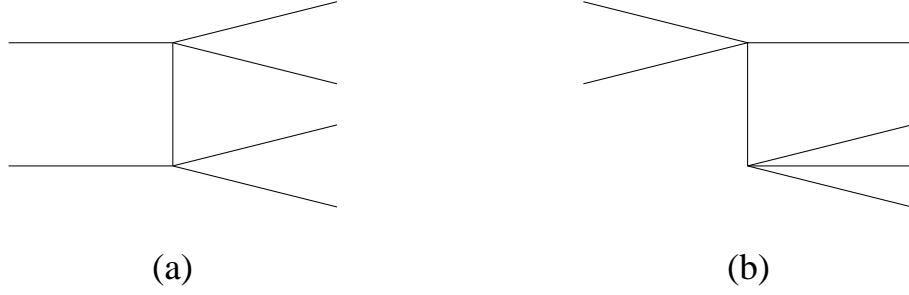


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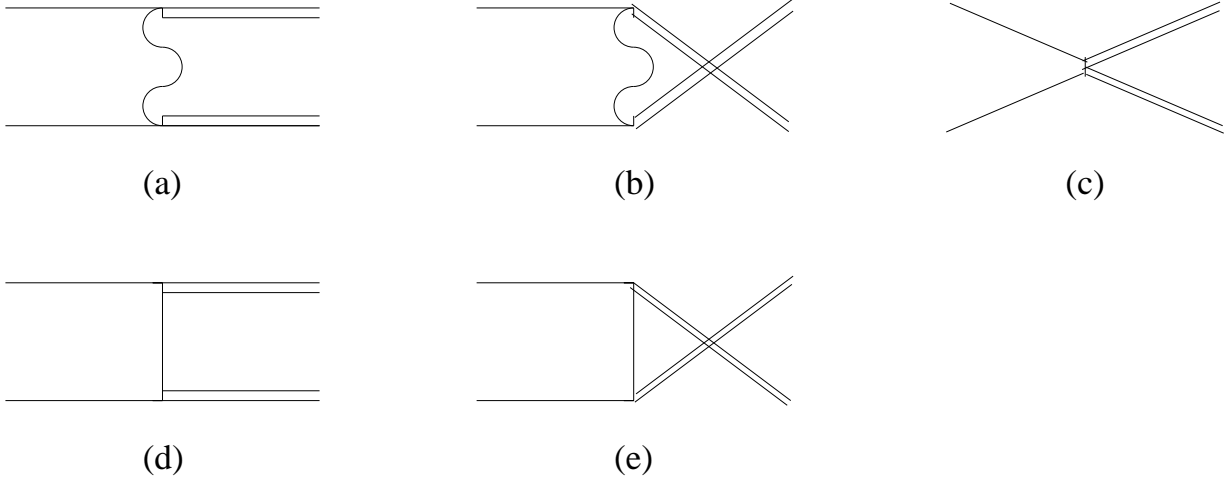


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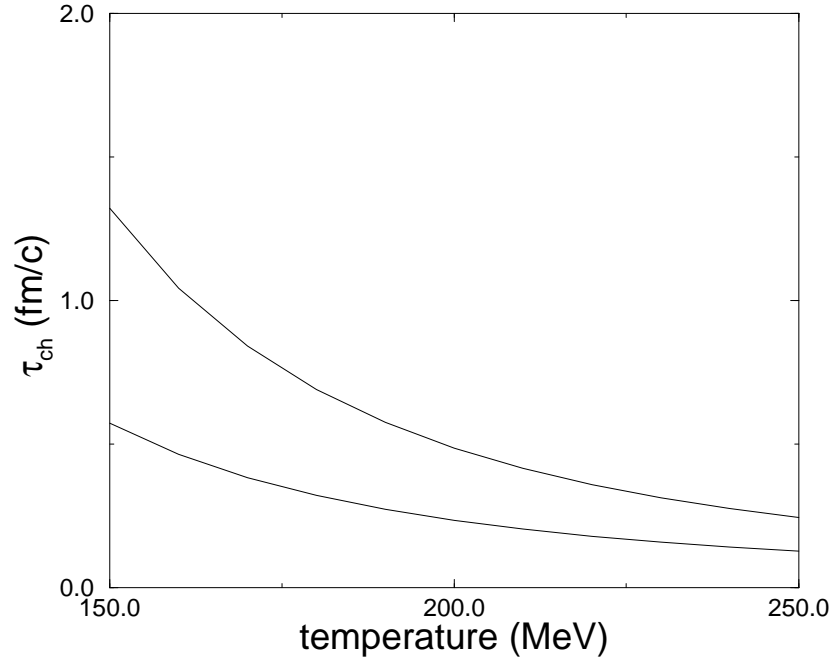


Figure 3: Chemical relaxation time of pions at finite temperature. The results are obtained in the chirally symmetric phase with $m_\pi = m_\sigma = 140$ MeV and $m_\rho = m_{a_1} = 770$ MeV. Two different values of $\lambda = 21.4$ (lower), 7.62 (upper) are used.

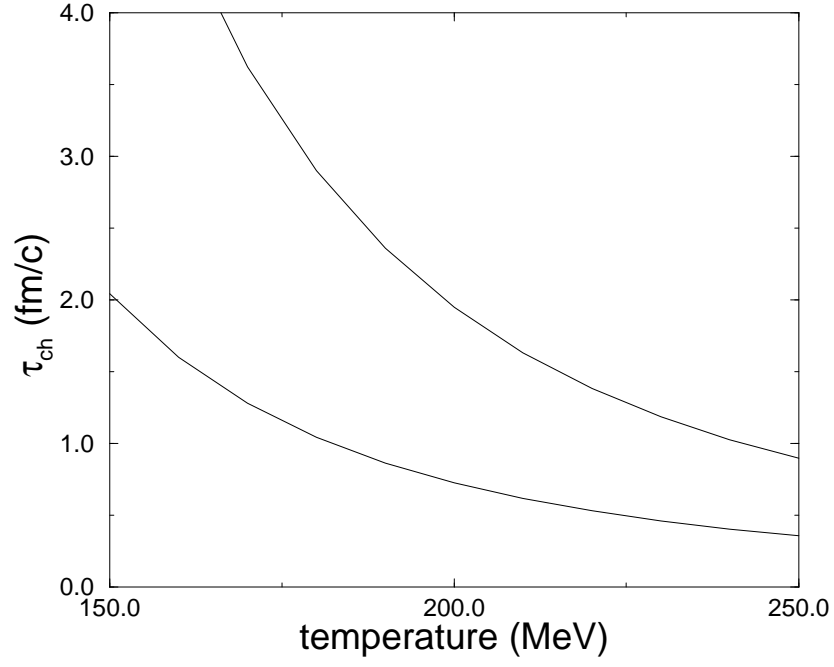


Figure 4: Chemical relaxation time of pions at finite temperature. The results are obtained in the chirally symmetric phase with thermal effects on the meson mass, $m_\pi = m_\sigma = 220\text{MeV}$ and $m_\rho = m_{a_1} = 980\text{ MeV}$. Two different values of $\lambda = 21.4$ (lower), 7.62 (upper) are used.